



An evaluation of performance of automatically operated multi-fuel downdraft gasifier for energy production



Nerijus Striūgas*, Kęstutis Zakarauskas, Algis Džiugys, Robertas Navakas, Rolandas Paulauskas

Laboratory of Combustion Processes, Lithuanian Energy Institute, Breslaujos Str. 3, LT-44403 Kaunas, Lithuania

HIGHLIGHTS

- The gasification of different types of pelletized fuel and waste was examined.
- Comparison of the process performance in a single automated gasifier was evaluated.
- The main parameter for process automation is the pressure drop threshold in a bed.
- Various pelletized fuels can be gasified in a single automated downdraft gasifier.

ARTICLE INFO

Article history:

Received 17 June 2014

Accepted 3 September 2014

Available online 16 September 2014

Keywords:

Downdraft gasification

Pelletized biomass

Pressure drop

Char

Process automation

ABSTRACT

Till now mainly commercially available downdraft gasifiers are constructed and developed for a clean and well prepared woody biomass, like wood chips. However, recently, wastes, such as sewage sludge, farm litter or harvested agricultural waste, are of great interest to end users. Desirable that facility like gasifiers could be able to recognize different waste types and properly adapt to the required processes.

The paper presents the results of experimental investigations in a downdraft gasifier using different types of fuel and waste to compare process performance and estimate the potential to gasify various feedstock types in a single fully automated device. Several types of feedstock were used in investigations: wood chips, pellets from wood, rape straw, poultry litter, dried sewage sludge and their mix with wood. The experimental analysis evaluates and reveals the differences in process parameters such as temperatures, pressure drop of a bed, products composition and yields, process efficiencies associated with the gasification of various feedstock. Established, that the proper automation of multi-fuel downdraft gasifier should contain a residual discharge and fuel feed control according to optimized the pressure value, whereas air flow supply automation is possible due to staged air adjustments and must be followed by a char discharge system.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

For small industrial plants in small countries like Lithuania that do not possess fossil fuel resources, small capacity (1–4 MW) gas generators are a subject of great interest. Fixed bed downdraft gasifiers are most suitable for the production of gas on small scales [1]. Historically, most downdraft gasifiers were designed to gasify large-sized woody fuels [2]. However, recently, wastes, such as sewage sludge, farm litter, and harvested agricultural waste, are of great interest to end users. The shape of various obtained wastes

mostly there are in the form of small particles that need to be correctly pretreated before being used in a gasification unit. The most common pre-treatment is still to either perform pelleting or briquetting processes on the material [3].

The downdraft gasification of the larger-sized biomass is not cumbersome for process performance, whereas small pieces increase the complexity. First, fine particles change the fluid dynamics of the gasification process. The pressure drop across the gasifier bed increases with a decrease in the amount of char particulates present in the reduction zone so that the dominating factor becomes the char bed porosity. Erlich and Fransson [4] maintain that the pressure drop should be higher when using more reactive fuel pellets, such as wood. Therefore, the temperature in the combustion zone increases, which leads to more intense

* Corresponding author. Tel.: +370 37 401877; fax: +370 37 351271.

E-mail address: Nerijus.Striugas@lei.lt (N. Striūgas).

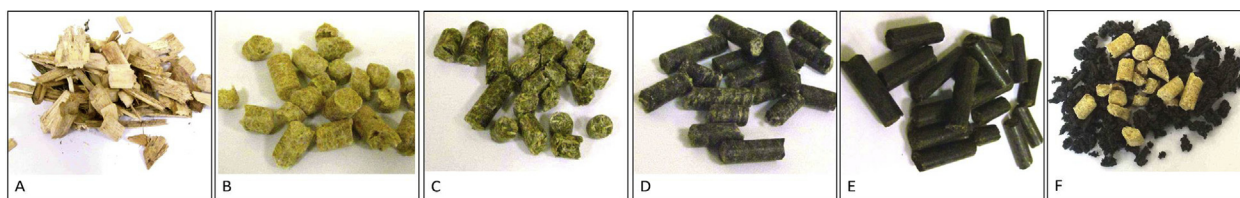


Fig. 1. Feedstocks used in experimental investigation: A – wood chips; B – wood pellets; C – rape straw pellets; D – poultry litter pellets; E – sewage sludge-sawdust pellets (70 ÷ 30 wt.%); F – mix of sewage sludge/wood pellets (50 ÷ 50 wt.%).

reduction reactions and causes the production of smaller char particulates. Simone et al. [5] experimentally analyzed the gasification of pelletized wood sawdust mixed with sunflower seeds in a 200 kW_{th} downdraft gasifier. Significant attention was paid to the evaluation of the pressure drop across the bed. The pressure drop behavior was found to depend on several factors: first, the bed material and fuel morphology and, second, the producer gas flow rate. Additionally, the same researchers [6] revealed a new factor enabling the means to control the frequency of the char discharge and presented optimal values for their gasifier. However, they concluded that the pelletized biomass is not an ideal material for downdraft gasifiers because of the very unstable and variable bed resistance, which causes problems for gasifier controls and generates significant residue. Similar conclusions made by Prasad et al. [7] even at gasification of larger sized pellets.

The next problem related to fine particles is the process temperature. The gasification process temperature is directly related to the air equivalence ratio (ER); i.e., more air leads to higher combustion temperatures. However, during the gasification of fine fuel, air access becomes limited because of the pressure drop. For the gasification of larger-sized fuels, such as wood briquettes or even wood chips, the gasification temperature should be kept as high as possible due to the low resistance of the layer. For instance, Olgun et al. [8] performed an experimental study on a downdraft gasifier system where wood chips and hazelnut shells were used as the fuel. From these experiments, it is evident that the authors could easily achieve temperatures of 1200 °C at ER = 0.35. The large-dimension (20 × 10 mm) feedstock made from oil palm fronds was tested in a 50 kW downdraft gasifier [9]. The effect of temperature over the range of 500 to 1200 °C was studied. The authors concluded that the higher temperatures in the combustion zone favor endothermic reactions where CO₂ and H₂O are consumed and combustible gases with higher concentrations of CO are produced via reactions with

residual C. The optimal ER was identified as 0.37, which corresponded to a carbon conversion efficiency of 93%. Similar results were obtained for the gasification of other feedstock types including furniture wood and wood chips [10]. Compared to the pelletized fuels gasified in downdraft reactors, the range of temperatures varies. The maximum temperatures that have been achieved are 700–1200 °C by Erlich and Fransson [4], 1104 °C by Simone et al. [5], 600–850 °C by Yoon et al. [11] and 600–1000 °C by Kyriakos et al. [12]. The temperature depends on gasifier, feedstock types and working parameters but is generally lower; otherwise, the bed resistance increases considerably. At higher ERs, the pressure drop may exceed 0.6 kPa [4] or even reach 5 kPa [5]. The pressure drop may be a few times smaller when compared to that of larger feedstock [13].

The literature review shows that gasification of different feedstock in downdraft gasifiers entails certain difficulties. The nature of the feedstock may impose a maximum temperature limit, the fluid dynamics and pressure drop fluctuation, variation in product composition, overall gasification process efficiency or feedstock conversion ratio. The variation of process parameters leads to the difficulties for the proper and reliable automated control of gasification process. The mentioned restrictions limits the availability of commercial fuel-flexible and self-controlled small-scale gasifiers. The latest research in downdraft gasification shows the trend on system automation [14] or [15], but mostly dedicates to a single well-defined feedstock sort. It is desirable that facilities like gasifier could be able to recognize different feedstock types and properly self-adapt to the required processes. Therefore, the purpose of this work is to perform experimental investigations of gasification process in a downdraft gasifier using different types of fuel and waste in order to compare process performance and estimate the feasibility of gasification of various feedstock types in a single automated self-controlling device.

Table 1
Characteristics of feedstock used in experimental investigation.

Parameter	Mixed wood chips	Softwood pellets	Rape straw pellets	Poultry litter pellets	Sewage sludge-sawdust pellets	Mix of sewage sludge/wood pellets
<i>Proximate analysis wt.%</i>						
Moisture	10.6	5.2	14.9	7.6	4.4	4.0/5.2
Volatiles	75.8	79.2	62.5	63.6	59.5	51.1/79.2
Fixed carbon	12.8	15.2	17.2	15.3	14.3	13.9/15.2
Ash	0.8	0.4	5.4	13.5	21.8	31.0/0.4
HHV (MJ/kg)	17.3	19.0	16.2	16.8	17.8	17.3/19.0
<i>Ultimate analysis wt.% (dry basis)</i>						
Carbon	48.77	49.20	39.60	43.98	41.08	40.05/49.20
Hydrogen	5.85	6.20	5.60	5.16	5.51	5.15/6.20
Oxygen (diff.)	44.52	44.06	48.54	31.98	26.90	16.40/44.06
Nitrogen	0.05	0.08	0.78	4.63	3.77	5.85/0.08
Sulfur	0.01	0.06	0.08	0.75	0.94	1.55/0.06
Ash softening temperature, °C	1270	1315	1067	1290	1158	1106/1315
Fuel particulates, mm	20–50	8	8	8	8	3–10/8

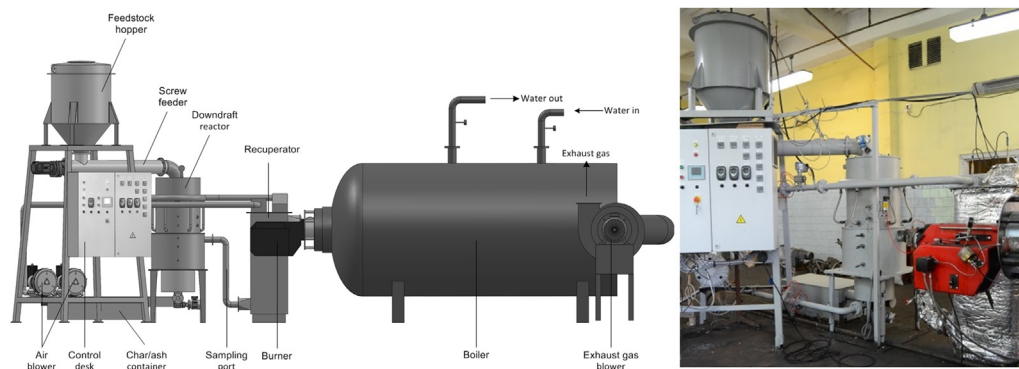


Fig. 2. Scheme and photo of the experimental setup.

2. Material and methods

2.1. Biomass characteristics

Several types of feedstock were used in these investigation: wood chips (WC), pellets made from softwood sawdust (WP), rape straw (SP), poultry manure with litter from softwood sawdust (PP), dried sewage sludge (70 wt.%) mixed with softwood sawdust (30 wt.%) (SSP) and dried sewage sludge (50 wt.%) mixed with softwood pellets (50 wt.%) (SSW) (Fig. 1). The characteristics of the feedstocks are presented in Table 1. Feedstock analyses were performed using an IKA C5000 calorimeter, a Flash 2000 CHNS analyzer and a NETZSCH STA 449 F3 Jupiter thermogravimeter.

2.2. Experimental setup

The scheme and photo of experimental setup is presented in Fig. 2. The system consists of four parts: the biomass feed system,

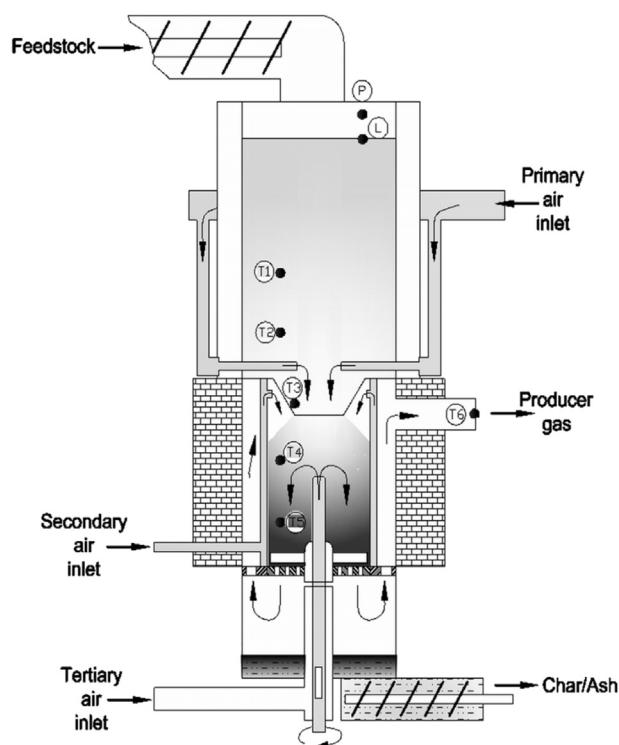


Fig. 3. Scheme of the experimental downdraft reactor T1–T6 – temperature sensors; P – pressure sensor; L – level sensor.

the downdraft gasifier, the heat recuperator and a boiler with a burner. The feedstock is supplied to the gasification reactor from the hopper by a screw feeder that moves downward in a tightly closed vessel. A custom developed mechanical level measuring device automatically maintains a constant feedstock level in the reactor. The air necessary for combustion is supplied by a blower directed perpendicularly around the combustion zone so that the required temperature is maintained over a small height range. The residual char is additionally gasified by secondary and tertiary air supplies. The residue from the gasification process, including char and ash, is extracted through a moving grate and stored in a char/ash container. Producer gas flows through the char that accumulates at the bottom of the reactor and travels upward through insulated pipes to the heat recuperator to pre-heat the primary air. The partially cooled producer gas exiting the recuperator is directed to the burner inside a VK21 water heating boiler. A Bentone company B40A liquid fuel burner is used in the boiler. The burner is modified for the co-combustion of producer gas via special orifices that are installed to inject the producer gas into the burner. An exhaust gas blower discharges the combusted gas into the atmosphere through a smoke stack. The entire gasification process is automated and self-controlled from a control desk installed outside the reactor. The main operating parameters are collected and stored in a remote computer.

The gasification reactor was designed according to known published technologies [16]. A detailed explanation is presented in Fig. 3. The throat diameter was 130 mm. The diameter of the tuyere position in reactor was 200 mm, according to experimental results. The height between the tuyeres and the throat was 110 mm. The diameter of the reactor above the throat was 400 mm. Although the real working diameter depends on the immersion of the tuyere, at the current position the real working diameter was approximately 250 mm. The remainder of pelletized feedstock behaves as thermal insulation. The diameter of the reduction zone is 300 mm. The height of the upper part of the reactor is 600 mm. The height of the reduction zone is 430 mm. The improvements introduced in this work include the restricted char reduction zone with walls and a moving grate at the bottom. This allowed for full control over the discharge of the char/ash mixture and ended the necessity to sweep out of the light char particles. The second addition was the introduction of a staged air supply to maintain a high and uniform temperature in the reduction zone. Other gasifier design parameters are presented in Table 2.

2.3. Principle of gasifier system automation

The gasifier automation is based on the closed loop PID control system. Three main loops are implemented to control main

Table 2
Design parameters of gasifier.

Parameter	Value
Fuel consumption, kg/h	50
Heat capacity (according fuel), kW	250
Air equivalence ratio (ER)	0.25
Stoichiometric air at ER, Nm ³ /h	60
Maximum staged air flows, Nm ³ /h:	
primary	50
secondary	15
tertiary	30
Producer gas yield, Nm ³ /kg	2
Superficial velocity, m/s:	
throat	2.1
reduction	0.4
Cold gas efficiency	0.75
Heart load, MW/m ²	14

parameters such as air supply, feedstock feeding and char/ash discharge.

A simple PID controller implements the automation of the air supply where the output signal adjusts the frequency of the air blower. The primary and secondary air flows are set to be constant, the values indicated in Table 3. The threshold of the tertiary air flow is set automatically according to the maximum allowed temperature in the reactor and pressure drop over the bed. According to the identified material characteristics (Table 1), particularly the ash softening temperature, the maximum (1000 °C) possible gasification process temperature is selected. The maximum process temperature plays a role in the correction factor for the tertiary air flow control. When the temperature reaches a certain set point, the additional air supply to the reactor is disabled.

For the feedstock automated feeding, the mechanical level measurement device equipped with two laser sensors was developed to carefully follow the feedstock level inside the reactor. Because the reactor works under pressure, laser sensors were installed in the outer side of the reactor. Such a design prevents the

contamination of sensors with tar, water condensation and/or dust. The laser sensor follows the movement of the lever, the minimum–maximum positions are recorded, and the ON/OFF signal is sent to the screw feeder motor. The empty space between the screw feeder and the maximum position of feedstock inside the reactor is always maintained so that blockages from swelling of the pelletized fuel are avoided [17].

The char discharge system consists of a movable grate and a screw conveyor for transporting the char to the storage tank. The conveyor works constantly and the movable grate works periodically. A signal from the pressure sensor (P) is processed through a PID based controller in which the adjustable variable is a pause between the working periods. The grate working period is set to 3 s. For all of the tested types of feedstock, the set point pressure was 3 kPa. The optimal pressure level of 3 kPa, for the presented modification of gasifier, was determined experimentally by manually controlling the gasifier. Determined, that a higher pressure results in an unstable operation of device with cyclical expelling a higher amount of producer gas, temperature variation and leaks; while a decrease in the pressure leads to an increase in the unreacted fuel content.

2.4. Product sampling and analysis

The producer gas samples were taken and analyzed using the Agilent 7890A gas chromatograph with two-channel heat conduction detectors (TCD) and a set of valves. The first channel was used for separation of the O₂, N₂, CO₂, CH₄, CO and light hydrocarbons, and the parallel second channel was used for H₂ separation. The species are detected based on the retention time of the specific species identified by calibration.

In the course of the experiments, the samples of the condensable species (tars) are taken simultaneously with the gas samples. A standard technique is used based on tar condensation in the solvent to determine the tar concentration in the gas flow exiting the

Table 3
Comparison of gasification performance of different feedstock.

Parameter	Mixed wood chips	Softwood pellets	Rape straw pellets	Poultry litter pellets	Sewage sludge-sawdust pellets	Mix of sewage sludge/wood pellets
Fuel load, kg/h	63	57	47	30	28	50
Air flow, Nm ³ /h:						
primary	61	55	49	55	49	57
secondary	30	30	30	30	30	30
tertiary	5	5	5	5	5	5
Air equivalence ratio (ER)	0.21	0.20	0.29	0.41	0.39	0.24
Gas, Nm ³ /h	130	122	109	90	87	113
Gas yield, Nm ³ /kg	2.06	2.14	2.32	3.00	3.11	2.26
Average gas composition, vol.%:						
H ₂	16.40	14.01	14.43	14.55	14.00	10.37
CO	22.60	24.27	14.59	17.42	16.40	19.01
CH ₄	4.80	4.12	4.06	1.29	1.05	7.14
C ₂ H ₂	0.11	0.13	0.09	0.07	0.06	0.10
C ₂ H ₆	0.08	0.11	0.06	0.04	0.05	0.08
C ₃ H ₈	0.06	0.03	0.03	0.03	0.02	0.06
CO ₂	11.05	10.26	11.8	13.51	9.20	10.10
N ₂	44.90	47.07	54.96	53.09	59.22	53.14
Gas LHV, MJ/Nm ³	6.50	6.21	4.97	4.32	4.04	6.23
Char yield, kg/h	3	6	6	2.5	4	5
Carbon content in char, wt.%	82.10	84.32	55.43	32.41	34.92	42.76
Tar, g/Nm ³	0.43	3.31	0.41	1.11	1.24	2.15
Superficial velocity, m/s:						
throat	2.72	2.55	2.28	1.88	1.82	2.37
reduction	0.51	0.48	0.43	0.35	0.34	0.44
Cold gas efficiency, %	82.7	75.1	75.3	80.7	75.4	82.7
Hot gas efficiency, %	90.4	81.7	83.7	90.8	86.2	89.8
Heart load, MW/m ²	19.78	17.68	13.00	9.57	8.85	16.42

reactor. The obtained tar samples are weighted and analyzed by a Varian GC-3800 gas chromatograph equipped with a flame ionization detector.

After each experiment, the char yield is weighted and carbon content using a Flash 2000 CHNS analyzer is measured.

3. Results and discussion

The aim of this work is to compare the performance of the constructed gasifier for production of substitute gas from various types of biomass and waste. Due to the limited volume of the feedstock hopper (0.3 m³), the experiments lasted no longer than four hours. After 1 h of operation the gasification process becomes stable (Fig. 4) and the main parameters of the gasification device were evaluated (Table 3). The only parameter a pressure drop (subsection 3.1) in the reactor was analyzed when operating at a dynamic gasification mode.

3.1. Pressure drop

For pelletized or small particles containing feedstock gasification, the bed pressure drop becomes a very important process parameter. An example of how the pressure and temperature change in a reactor by varying air flow is shown in Fig. 4 for softwood pellets gasification. From the initiation of the gasification process at 9 h 00 min, the process occurred with automated grate control when the set point of reactor pressure was 3 kPa. After the parameters of stable gasification mode were acquired, at approximately 12 h 15 min, the automated control of grate was changed to manual to investigate the pressure drop behavior as a function of the air flow. At first, the primary air set point increased from 30 to

35 Nm³/h. As the air flow through the bed increased, the reactor pressure began to increase as well. At this point, a new pressure set point of 4 kPa was set in the reactor control panel to trigger the automated grate. After the increase in the primary air flow, the temperature at T3 increased by ~100 °C. The other temperatures remain unchanged. After ~40 min, the set point of the primary air was changed from 35 to 30 Nm³/h, and the secondary air set point was changed from 5 to 15 Nm³/h. In this way, the pressure drop reached almost 5 kPa. That implies that the pressure set point should be changed again to avoid residual char augmentation. An increase to the secondary air flow increases the temperature at T4 in the reduction zone. Some temperature increases are seen also in the zone where thermocouples T5 and T6 are located. This experiment clearly shows the effect of the pressure drop on the change of the flow through the packed bed.

3.2. Temperatures

The internal reactor temperatures during the gasification of various feedstocks are shown in Fig. 5. At gasification of larger fractions fuel (wood chips) the highest temperature of 1100 °C was determined. The maximum temperature was measured by the T3 thermocouple installed in the throat of the combustion zone. During gasification of pelletized feedstock, this temperature oscillated between 800 and 850 °C. The main factor limiting the temperature was that the predetermined operating pressure in the reactor achieves 3 kPa. Subsequently the discharge system changes the adjustable variable and removes more of char. Higher temperatures led to larger amounts of gaseous products and more intense gasification of the char residue. However, previous experiments showed that after the pressure exceeds a certain threshold, the reactor becomes unstable and difficult to control.

Due to intensive gasification reaction of hot char, the temperatures at the T4 and T5 thermocouples (Fig. 5) are lower than that at T3 for all cases, even though additional air is supplied to the reduction zone. However, one difference stands out: the higher the ash content in the feedstock, the smaller the temperature drop in the reduction zone (Fig. 6). As the heat absorption decreases due to the less intensive char gasification reactions, the flue gas temperature T6 rises.

As seen from the temperature fields, the softening temperatures were not exceeded and agglomeration of melted particulates was avoided for any of the tested feedstocks. The main reason preventing the particle agglomeration is right selection of the pressure in the reactor and additionally, air staging avoids the creation of local high-temperature zones.

3.3. Fuel and air

When different fuel types are used, the amount of feedstock capable of being supplied to the reactor changes depending on the upper pressure threshold. As the ash content in the feedstock increases, the maximum fuel load decreases to 28 kg/h (SSP) from the maximum of 63 kg/h (WC) or 57 kg/h (WP). This leads to a lower total producer gas flow, despite the yield of gas per kilogram of feedstock increasing. This occurs due to an increase in the air equivalence ratio because of the smaller amount of feedstock.

During the experiments, the primary air flow remained constant at 30 Nm³/h for all cases. Further increases to the air flow do not directly cause temperature increases, only the demand for fuel increases. As the amount of feedstock increases, the heat produced by combustion is used for fuel volatilization and produces higher amounts of char, which further cause the pressure increase.

At constant primary air flow, the temperature in the combustion zone always exceeds 800 °C for all tested fuel types. Therefore, this

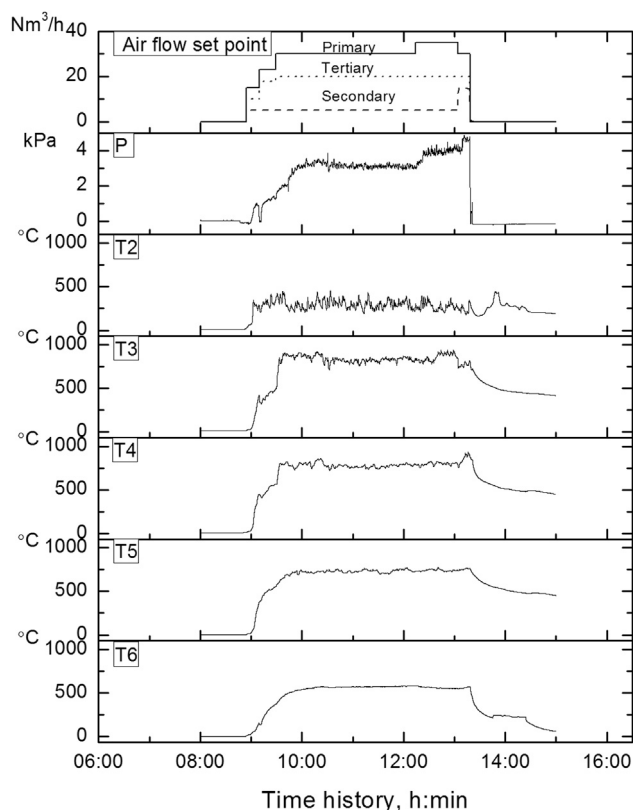


Fig. 4. The profiles of reactor pressure and temperatures at the different set point of air flow. Feedstock – softwood pellets.

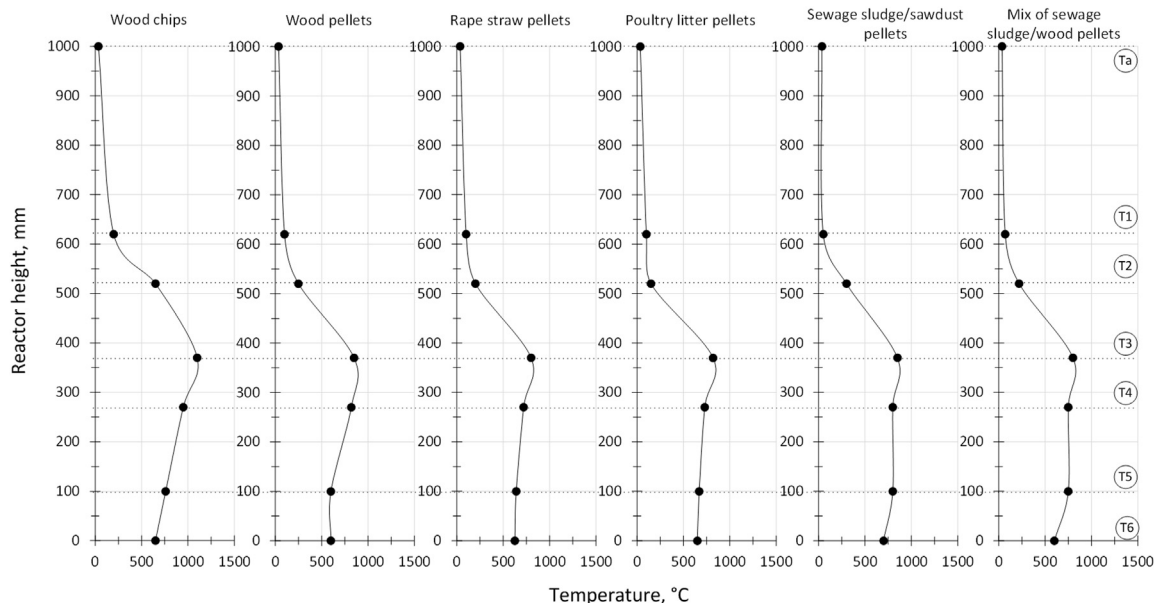


Fig. 5. Temperature fields in an experimental downdraft reactor during gasifying various feedstocks.

temperature threshold is sufficient for producing char without volatiles. An additional task is the efficient reduction rate of char, which depends greatly on the process temperature [18]. To achieve a high temperature in a continuously moving, low-porosity bed is difficult and requires a considerable amount of energy. However, this process is not complicated in empty spaces. The intent of the secondary air supply is to achieve high temperatures in the empty local space by combusting a part of the producer gas. This temperature is very easy to control and depends directly upon the supplied amount of air (Fig. 4, thermocouple T4). To avoid clinker formation due to the high ash content of some tested materials, the amount of secondary air was set to 5 Nm³/h. This resulted in the temperature in this zone varying between 720 and 820 °C for pelletized fuel and reaching approximately 950 °C for wood chips. The difference in temperature may be due to the overall heat balance of the process. If a producer gas at a higher temperature enters from the combustion zone, less heat is required to achieve a higher temperature.

The tertiary air was left as a variable to control the optimal condition between the pressure drop in the reactor and amount of the residual char. Additionally, the tertiary air oxidizes part of the

producer gas to produce more heat for the intensification of the endothermic char gasification reaction.

3.4. Producer gas

The averaged producer gas composition, as shown in Table 3, differs for all of the tested feedstocks. The composition of the gas produced from wood chip gasification in this work agreed with that in Ref. [1]. The hydrogen content was highest compared to other tests using pelletized fuel. This may be related to the higher temperatures in the process and the more complete destruction of tar constituent containing greater amounts of hydrocarbons. The calculated net calorific value (LHV) (1) of the producer gas from wood chip gasification is equal to 6.5 MJ/Nm³.

$$\text{LHV} = 10.792\text{H}_2 + 12.636\text{CO} + 35.818\text{CH}_4 + 56.469\text{C}_2\text{H}_2 + 64.046\text{C}_2\text{H}_6 + 93.185\text{C}_3\text{H}_8 \quad (1)$$

For pelletized wood, the gas composition was slightly different than for bulk wood: the hydrogen concentration decreased to 14.01 vol.%, and the methane concentration decreased to 4.12 vol.%, but the CO concentration increased to 24.27 vol.%. The LHV decreases slightly to 6.21 MJ/Nm³.

For the gasification of rape straw, poultry litter and sewage sludge-sawdust pellets, the concentration of hydrogen in the producer gas remains at 14 vol.%. The concentration of carbon monoxide varied slightly (see Table 3). The highest difference noticed was the concentration of methane. The average CH₄ volumetric concentration of 4.06 vol.% for rape straw was very similar to that obtained from gasification of woody feedstock, whereas for the pellets produced from poultry litter and sewage sludge, the concentration decreased to 1.29 and 1.05 vol.%, respectively. The main reason for the methane concentration difference may be the higher ERs, in the range of 0.41 and 0.39, compared to a previous range of 0.20–0.29 for other runs. More complete oxidation may primarily burn the gaseous products or provide extra steam for the steam reforming reaction. The highest methane concentration was produced in the gasification experiment using a mix of dried sewage sludge/wood pellets. It was determined that the average methane

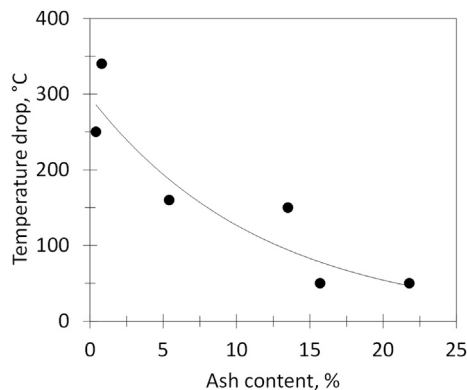
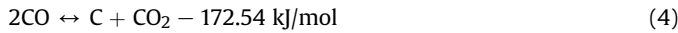
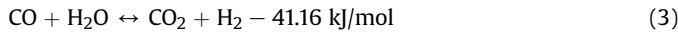
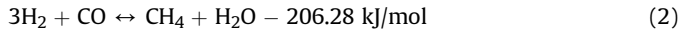


Fig. 6. The behavior of the temperature ($\Delta T = T_3 - T_5$) drop in the reduction zone versus the ash content in the feedstock.

concentration in producer gas was 7.14 vol.%. The cause of the high methane yield is the methanation reaction that may occur via a series of complex of reactions [19,20]:



After the methanation reaction, the additionally produced methane increases the calorific value to 6.23 MJ/Nm³, compared to the case of pelletized sewage sludge where the calorific value was only 4.04 MJ/Nm³.

3.5. Solid residues

The residual char content is the key factor that demonstrate the efficiency of the feedstock conversion to a gaseous product. The remaining hot char not only reduces the efficiency of gasifier but also makes utilization troublesome for end users. In this work, the smallest amount of char of 4.8 wt.% observed during the gasification of wood chips (Table 3). For a feedstock using pelletized fuel, the amount of char remaining was higher and varied between 7.8 and 14.3 wt.%. The main contributor to the char yield was the temperature field in the reactor and the pressure drop across the bed.

The carbon content decreases with increasing ash content in the feedstock (Table 3). The highest carbon content was obtained for the gasification of both pelletized and chipped wood and was 84.32 and 82.1 wt.%, respectively. The smallest carbon content was found in the char from the poultry litter pellets. Although the ash content in the raw material was not the smallest of the tested feedstocks, the amount of residual char was smaller than in cases with high ash content fuels. The main reason for this was a more complete reduction of the char, which led to less residual material per fuel load.

3.6. Energy balance

An analysis of energy balance was carried out, and the cold and hot efficiencies were calculated to evaluate the performance of the downdraft gasifier for different feedstocks.

Fig. 7 shows the distribution of the energy output for the different feedstocks. The main part of the chemically bound fuel energy is transformed to chemical energy in the producer gas. The transformation of energy to cold gases from WC and SSW was 81%. For WP, SP, PP and SSP the transformation percentage was 74, 73, 78 and 72%, respectively. The incomplete carbon conversion (residual char) leads to higher energy losses. If there was no residual char, the energy output to the producer gas could reach almost 89% for all feedstocks, considering the same sensible heat value of the gas. The other energy losses depicted in Fig. 7 account for the sensible heat of the char, both the sensible and chemical energy of the tar, energy losses through the walls of reactor and all do not exceed the value of 3%.

The cold gas efficiency η_{CG} was calculated for two cases with (w/) and without (w/o) the heat recuperator. With the heat recuperator, the efficiency is calculated using the following formula:

$$\eta_{CG}^{w/} = \frac{V_G \text{LHV}_G}{M_F \text{LHV}_F} 100\% \quad (5)$$

where V_G is the producer gas flow (Nm³/h), M_F is the feedstock feed rate (kg/h), LHV_G is the lower heating value of the producer gas (kJ/Nm³), and LHV_F is the lower heating value of feedstock (kJ/kg).

When operating gasifier with heat recuperator a part of the heat is returned with preheated air. Consequently, less amount of fuel

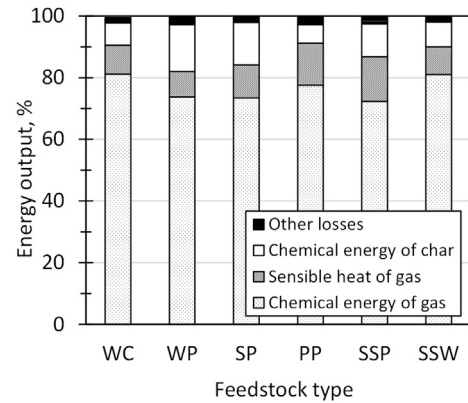


Fig. 7. The distribution of energy output for different feedstock.

energy is required to rise the reaction temperature to an appropriate level. The recovered amount of heat (Q_A) is calculated as follows:

$$Q_A = V_A c_{pA} (T_{Ar} - T_0) \quad (6)$$

where V_A is the volumetric primary air flow (Nm³/h), c_{pA} is the specific heat of air (kJ/m³ K) and T_0 and T_{Ar} are the air temperatures before and after recuperator (K), respectively.

In this work, no experimental tests were performed to investigate the influence of the heat recuperator on the gasifier performance. Thus, the cold gas efficiency of gasifier operating without the heat recuperator is calculated with the assumption that the recovered amount of energy is equal to additional feedstock energy, which is required to yield the same amount of energy output:

$$\eta_{CG}^{w/o} = \frac{V_G \text{LHV}_G}{M_F \text{LHV}_F + V_A c_{pA} (T_{Ar} - T_0)} 100\% \quad (7)$$

Fig. 8a shows the variation in the cold gas efficiency for different feedstocks. The highest cold gas efficiency without recuperation of 81.2% was achieved for WC run. The lowest efficiency of 72.3% was achieved at gasification of pelletized sewage sludge/sawdust mix (SSP). By introducing heat recuperation, extra heat is recovered, and depending on feedstocks LHV_F from 1.0 to 1.2 kg/h of the fuel is replaced. Accordingly, the cold gas efficiency increases with the increase of recovered heat in the primary air. Despite the air flow through the recuperator being kept constant for all experiments, the producer gas flow and temperature varied (Table 3 and Fig. 5). This led to different amounts of recovered energy. The minimum observed increase in efficiency was 1.4% for WP, whereas the maximum observed increase in efficiency was 3.1% for SSP.

The presented gasifier system is configured for producer gas combustion without being cooled to function with boilers or furnaces. Therefore, the hot gas efficiency, by taking into account the sensible heat of producer gas, has a greater impact on the evaluation of gasifier performance. With the same assumption as in calculations of cold gas efficiency, the hot gas efficiency η_{HG} was calculated for two cases with (8) and without (9) heat recuperation:

$$\eta_{HG}^{w/} = \frac{V_G \text{LHV}_G + V_G c_{pG} (T_{Gr} - T_0)}{M_F \text{LHV}_F} 100\% \quad (8)$$

where c_{pG} is the specific heat of producer gas (kJ/m³ K), T_0 is the temperature at STP conditions (K), and T_{Gr} is the gas temperature after recuperator (K).

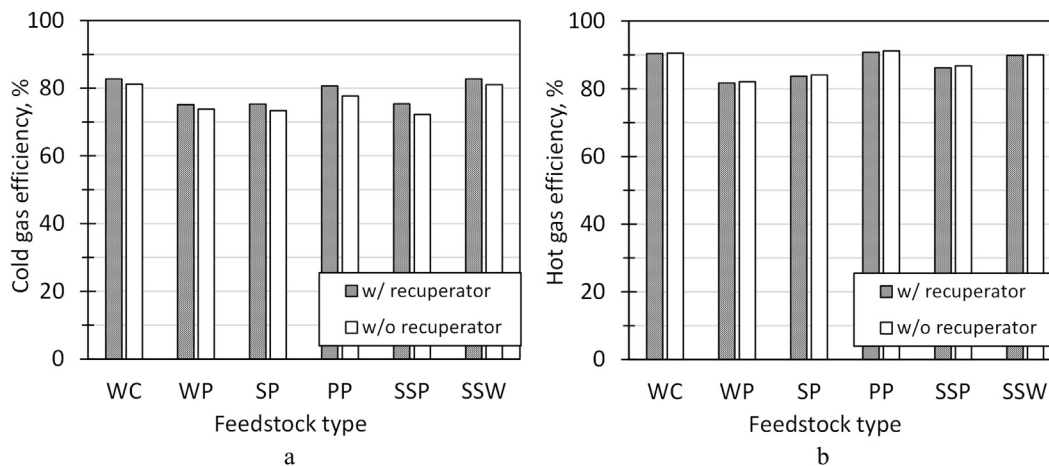


Fig. 8. The cold (a) and hot (b) gas efficiency w/ and w/o heat recuperator for different feedstock.

$$\eta_{HG}^{w/o} = \frac{V_G LHV_G + V_G C_{pG} (T_G - T_0)}{M_F LHV_F + V_A C_{pA} (T_{Ar} - T_0)} 100\% \quad (9)$$

where T_G is the gas temperature at the exit of gasifier (K).

The calculated hot gas efficiency results are presented in Fig. 8b. The sensible heat of the hot gases increases the efficiency from 6.6 to 10.9% for WP and SSP, respectively, compared with the cold gas efficiency without heat recuperation. After heat recuperation, the amount of sensible heat of the gas decreases with the preheating of the primary air. Accordingly, less of the feedstock is consumed, but the heat loss increases and the hot gas efficiency marginally decreases.

As the calculation of gasification efficiencies showed, when using the gasifier for direct heat and electricity production in an ICE or gas turbine, heat recuperation is essential. In the case of the direct combustion of the gas, the heat recuperator is not necessary. The preheated air does not influence the performance of the gasifier because the amount of recuperated heat is negligible compared with the heat generated by the partial combustion of the feedstock. If the additional heat can be provided from another source, such as high temperature steel or glass furnaces, the heat recuperator is still essential.

4. Conclusions

In this study, experimental investigations were performed in a throated downdraft gasifier with different types of non-pelletized and pelletized biomass and waste to compare the process performance and to estimate the possibility of gasifying various waste types in a single fully automated device. The experimental analysis revealed the differences of process parameters associated with the gasification of lump and pelletized fuel. The main differences between these types of feedstock are the temperature of the gasification process, the pressure drop and the residual content. For the gasification of larger feedstocks, such as wood chips, the maximum established reaction temperature was 1100 °C, whereas for pelletized biomass and waste, the temperature varied between 800 and 850 °C. The main reason preventing a higher temperature was to control the increasing pressure in the reactor. Lower process temperatures and automated pressure controls removing portions of the feedstock increase the residual char amount from 4.8 wt.% in the case of wood chips to 14.3 wt.% in the case of sludge/sawdust pellets. The producer gas composition and yield vary with the feedstock type in the range of 2.06–3.11 Nm³/kg with calorific

values of 6.5–4.04 MJ/Nm³. All of the above differences influence the process efficiency. The maximum cold gas efficiency of 82.7% was achieved for two runs using wood chips and a mix of sewage sludge/wood pellets. The lowest efficiency of 75.1–75.4% was determined for the remaining three types of pelletized fuels: wood, rape straw and sewage sludge-sawdust. The sensible heat of the hot gases increases the efficiency from 6.6 to 10.9%.

It can be concluded that although the process performance varies with the feedstock type, the selected preprocessed biomass and waste could be gasified in a single, properly automated downdraft gasifier. For the explored gasifier type, the main parameter influencing process automation is the pressure drop threshold in a bed, which depends on the nature and load of the feedstock, the amount of air flowing and the yield of generated producer gas. The residual discharge and fuel feed can be controlled according to optimized the pressure value, whereas air flow supply automation is possible due to tertiary air adjustments and must be followed by a char discharge system.

References

- [1] P. Basu, Biomass Gasification, Pyrolysis and Torrefaction, Practical Design and Theory, Academic Press, Boston, 2013.
- [2] B. Goldman, N. Clarke Jones, The mod portable gas producer, *Inst. Fuel* 63 (1939) 103–140.
- [3] M. Asadullah, Barriers of commercial power generation using biomass gasification gas: a review, *Renew. Sustain. Energy Rev.* 29 (2014) 201–215.
- [4] C. Erlich, T.H. Fransson, Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse. Experimental study, *Appl. Energy* 88 (3) (2011) 899–908.
- [5] M. Simone, F. Barontini, C. Nicoletta, L. Tognotti, Gasification tests of pelletized biomass in a downdraft gasifier, in: *Proceedings of 19th European Biomass Conference and Exhibition*, Berlin, 2011.
- [6] M. Simone, F. Barontini, C. Nicoletta, L. Tognotti, Gasification of pelletized biomass in a pilot scale downdraft gasifier, *Bioresour. Technol.* 116 (2012) 403–412.
- [7] L. Prasad, P.M.V. Subbarao, J.P. Subrahmanyam, Pyrolysis and gasification characteristics of Pongamia residue (de-oiled cake) using thermogravimetry and downdraft gasifier, *Appl. Therm. Eng.* 63 (2014) 379–386.
- [8] H. Olgun, S. Ozdogan, G. Yinesor, Results with a bench scale downdraft biomass gasifier for agricultural and forestry residues, *Biomass Bioenergy* 35 (2011) 572–580.
- [9] S.M. Atnaw, S.A. Sulaiman, S. Yusup, Syngas production from downdraft gasification of oil palm fronds, *Energy* 61 (2013) 491–501.
- [10] Z.A. Zainal, A. Rifau, G.A. Quadir, K.N. Seetharamu, Experimental investigation of a downdraft biomass gasifier, *Biomass Bioenergy* 23 (2002) 283–289.
- [11] S.J. Yoon, Y.I. Son, Y.K. Kim, J.G. Lee, Gasification and power generation characteristics of rice husk and rice husk pellet using a downdraft fixed-bed gasifier, *Renew. Energy* 42 (2012) 163–167.
- [12] Kallis X. Kyriakos, A. Giacomo, P. Susini, J.E. Oakey, A comparison between Miscanthus and bioethanol waste pellets and their performance in a downdraft gasifier, *Appl. Energy* 101 (2013) 333–340.

- [13] A. Kr. Sharma, Experimental study on 75 kW_{th} downdraft (biomass) gasifier system, *Renew. Energy* 34 (2009) 1726–1733.
- [14] C. Sagüés, P. García-Bacaicoa, S. Serrano, Automatic control of biomass gasifiers using fuzzy inference systems, *Bioresour. Technol.* 98 (2007) 845–855.
- [15] M. Stefanski, M. Siedlecki, A comparison between the classical control system and the neural network approach for the control of a small scale (800 kW_{th}) downdraft fixed bed biomass gasifier, in: *Proceedings of 21th European Biomass Conference and Exhibition: Copenhagen, 2013*.
- [16] T. Reed, B. Thomas, R.A. Das, A. Das, *Handbook of Biomass Downdraft Gasifier Engine Systems*, Biomass Energy Foundation, 1988.
- [17] R. Paulauskas, A. Džiugys, N. Striugas, L. Garšvinskaitė, E. Misiulis, Experimental and theoretical investigation of wood pellet shrinkage during pyrolysis, *Energetika* 60 (2014) 1–11.
- [18] I.I. Ahmed, A.K. Gupta, Pyrolysis and gasification of food waste: syngas characteristics and char gasification kinetics, *Appl. Energy* 87 (2010) 101–108.
- [19] J. Kopyscinski, T.J. Schildhauer, F. Vogel, S.M.A. Biollaz, A. Wokaun, Applying spatially resolved concentration and temperature measurements in a catalytic plate reactor for the kinetic study of CO methanation, *J. Catal.* 271 (2010) 262–279.
- [20] E.I. Koytsoumpa, K. Atsonios, K.D. Panopoulos, S. Karellas, E. Kakaras, J. Karl, Modelling and assessment of acid gas removal processes in coal-derived SNG production, *Appl. Therm. Eng.* (2014), <http://dx.doi.org/10.1016/j.applthermaleng.2014.02.026>.